

SYNTHESIS AND TESTING OF POWER OPTIMIZED WAVEFORMS (POW) WITH FOCUS ON 1-POW AND SQUARE POW

Santiago Hassig

SCHOOL OF PHYSICS

DR. GREGORY DURGIN
ADVISOR



ABSTRACT

Passive Radio Frequency Identification (RFID) tags are powered by energy-harvesting charge pumps through AC-to-DC rectification of the wireless RF signal: typically a pulse-interval encoded (PIE) continuous-waveform (CW). These charge pumps are comprised of capacitors and diodes, the latter being the leading barrier of passive tag operation. Specifically, the pump diode turn-on voltage is responsible for limited tag sensitivity, read range, and reliability. The Power Optimized Waveform (POW) is a new, non-invasive transmission signal that improves RFID tag sensitivity by providing higher peak voltages without exceeding Federal Communications Commission (FCC) output power regulations. Two POWs that are tested are the 1-POW, comprised of two sinusoids centered about a carrier signal frequency, and the Square POW, the product of a carrier signal and a voltage modulating square wave. A Dickson charge pump was used to measure the power gain of POW versus CW. Spectral efficiency and charge pump efficiency were calculated at different transmit powers and POW frequency spacing. Positive gain was achieved at low transmit powers ($< \sim 4$ dBm), and higher frequency spacing, making POW preferable over CW in low power applications.

POW
is a **NEW, NON-INVASIVE TRANSMISSION SIGNAL** that improves **RFID TAG SENSITIVITY** by providing **HIGHER PEAK VOLTAGES** without exceeding **FCC OUTPUT POWER REGULATIONS.**

RELATIONSHIPS

between **POW**
SUBCARRIER
FREQUENCY
SPACING,
PEAK POWER,
AVERAGE
POWER,
 and **PAPR...**
 attempts to
 explain the
EXPERIMENTAL
RESULTS and
 offers insight
 on **POTENTIAL**
APPLICATIONS
 for these
 particular
POWS.

I. INTRODUCTION

Power Optimized Waveforms within the Context of Radio Frequency Identification

Wireless power refers to the transmission of power from a source to a load without the use of wires. It is an emerging research field that has its roots in Radio Frequency Identification (RFID), where a passive tag with no local power source (i.e. no battery) must scavenge the power transmitted from a reader to turn itself on. Wireless power has many applications where limited power (e.g. no greater than a few milliwatts) is needed and a battery is either too large or too costly. Current applications include energy-harvesting devices such as sensors, personal area data devices, and other low-powered consumer electronics (Trotter, Griffin, & Durgin, 2009).

Devices that rely on wireless power, such as RFID tags, are characterized by their read range: the maximum distance a reader can be placed away from a tag while guaranteeing reliable reception of backscatter information. Conventional passive readers have a short read range (typically 2 to 10 m), which is related to their scavenging sensitivity. Ways to increase scavenging sensitivity include more sensitive circuit components, improving reader impedance matching, and switching to higher-gain antennas. Work in RF power harvesting has been done with power cycling of transmitter amplifiers to make signals such as a square waveform (Greene, Harrist, & McElhinny, 2008). However, this power cycling method does not optimize the bandwidth / Peak-to- Average-Power Ratio (PAPR) trade-off and it does not use the carrier as a full-duplex communications medium. Knowledge of this trade-off becomes especially useful when dealing with bandwidth limits such as those imposed by the Federal Communications Commission (FCC).

Transmitting Power Optimized Waveforms (POWs) is a new, non-invasive method for improving tag sensitivity (Trotter & Durgin, 2010a). A POW is specially designed to improve the power efficiency of the AC-to-DC power converter, known as a charge pump, when it is used as the input. The tag becomes more sensitive when its power efficiency increases.

This paper concentrates on the design, synthesis, and testing of two POWs: 1-POW and Square POW. The transmit power and subcarrier frequency spacing of each POW are varied and their performance assessed by comparing POW over continuous-waveform (CW) gain, spectral power efficiency, and charge pump efficiency. A discussion based on the relationships between POW subcarrier frequency spacing, peak power, average power, and PAPR, as developed by Trotter and Durgin (2010b), attempts to explain the experimental results and offers insight on potential applications for these particular POWs.

Charge Pumps and POW Waveforms

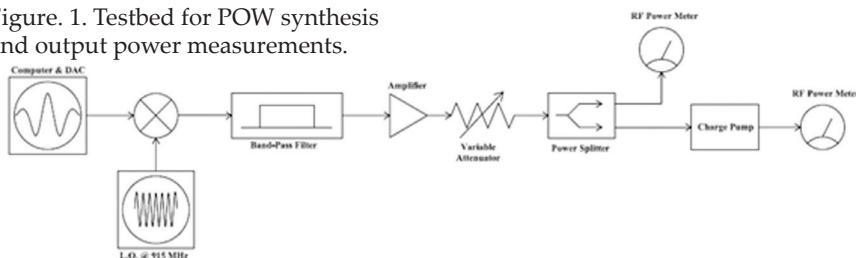
Passive RFID tags power themselves by rectifying the RF signal transmitted by a reader. A means of rectifying and boosting the RF power is through the inclusion of charge pumps in the tag. Specifically, the Dickson charge pump, which includes one or more serial stages of capacitors and diodes, is commonly used in RF-to-DC power conversion (Dickson, 1976). Charge pump diodes, however, introduce inefficiencies if the input RF voltage is not sufficiently large to trip the diodes.

A POW has a few basic properties when compared to the standard CW carrier used by RFID readers. Assuming the POW and CW carriers must have the same root mean square (RMS) voltage ensuring identical transmitted power, the POW has:

- Peak voltage that is much larger than its equivalent CW,
- Diode threshold voltages that are tripped more easily, and
- Capacitors that charge up to higher voltages (the key advantage of a POW over CW).

The POW period, which is closely related to the number of subcarrier frequencies and their separation, must not be too long or the charge pump capacitors will discharge and the tag will power off.

Figure 1. Testbed for POW synthesis and output power measurements.



II. METHODS

POW Testbed

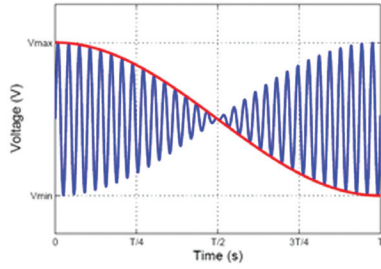
Two POW carriers were designed in MATLAB: a 1-POW and a Square POW. Each POW was synthesized by mixing the baseband frequencies with a 915 MHz local oscillator (L.O.) signal that was filtered to ensure a clean input signal. This signal was fed to an amplifier in series with a variable attenuator. The output from the variable attenuator was split and connected to a power meter and to the energy harvester's charge pumps. The variable attenuator controlled the POW transmission power input to the energy harvester. The setup is illustrated in Figure 1.

Transmission power and frequency spacing were varied independently to assess the effects that each parameter had on the following performance metrics:

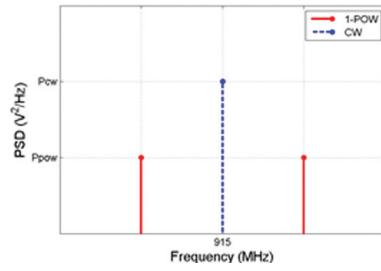
- POW gain,
- Spectral efficiency, and
- Charge pump efficiency.

The POW period...
MUST NOT BE TOO LONG or
the charge pump capacitors
will **DISCHARGE**
and the tag will
POWER OFF.

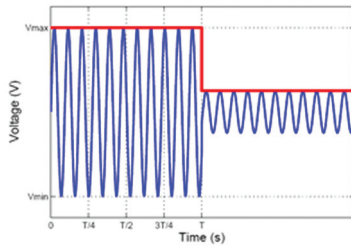
Figure. 2. Frequency- and time-domain plots of 1-POW and Square POW.



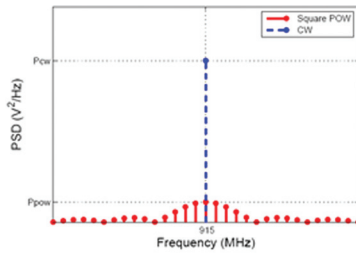
(a) 1-POW time domain



(a) 1-POW time domain



(b) 1-POW and CW power spectrum density



(c) Square POW time domain

In the first experiment, each carrier was fixed at a period of 1 μ s. Spectral power efficiency and gain were measured at different transmission powers. In the second experiment, transmission power was fixed (first at 4 dBm and then at 7 dBm) and charge pump efficiency and gain were measured at various POW frequency spacings.

Frequency and Time Domain Design of POWs

Two classes of power-optimized waveforms were examined: N-POW and Square POW. Each POW spectrum can be defined by its baseband version upconverted to the passband. This section defines the POW based on its parameters and presents the Peak-to-Average-Power Ratio (PAPR). The PAPR is a useful metric that describes the POW's ability to focus its power (Trotter, Hässig, & Durgin, 2010).

A. N-POW

The N-POW class comprises N equally spaced baseband subcarrier frequencies. The N-POW's baseband time-domain and power spectral density (PSD) equations are defined for $N > 0$:

$$V_{POW}(t) = \frac{1}{\sqrt{N}} \sum_{k=1}^N \cos(2\pi k \Delta f t) \quad (1)$$

$$PSD_{POW}(f) = \frac{1}{2N} \sum_{k=1}^N [\delta(f - k\Delta f) + \delta(f + k\Delta f)] \quad (2)$$

The simple case of the 0-POW is equivalent to the CW signal as it only has one frequency carrier (generally 915 MHz in the case of RFID). The upconverted 1-POW turns a baseband cosine waveform into a waveform of two cosines centered about the carrier frequency. The general N-POW is defined in Eq. 1. The equations for N-POW peak power, average power, and PAPR are:

$$\text{peak power} = 2N (V^2) \quad (3)$$

$$\text{average power} = \frac{1}{2} (V^2) \quad (4)$$

$$\text{PAPR} = 4N \quad (5)$$

For the N-POW, peak power is directly proportional to the number of subcarriers, while the average power remains the same. As a result, PAPR is also proportional to the number of subcarrier frequencies.

In the case of the 1-POW, the difference in subcarrier frequencies equals the POW frequency, Δf , and period, $1/\Delta f$. In the general case of N subcarriers, the POW frequency is equal to the lowest common multiplier of the differences between subcarrier frequencies. The downside of increasing the number of POW subcarriers, assuming that the bandwidth is held constant, is an increase in the POW period. The greater the POW period, the lower the frequency of POW peak voltage arrivals and therefore the longer the discharge time of the pump capacitors, which may adversely affect POW efficiency. Conversely, increasing spacing between subcarrier frequencies will result in a bandwidth increase and a POW period decrease. One period of the 1-POW is illustrated in Figure 2(a). The relative difference in PSD between CW and 1-POW is illustrated in Figure 2(b).

B. Square POW

The Square POW is created by multiplying a 915 MHz sine wave with a square wave envelope or, alternatively, convolving a sinc wave with an impulse at 915 MHz. A Square POW characterized by a high voltage (V_{high}), low voltage (V_{low}), period (TPOW), and duty cycle (D) is defined by the following time-domain and PSD equations:

$$V_{POW}(t) = V_{low} + \sum_{k=-\infty}^{\infty} (V_{high} - V_{low}) \text{rect}\left(\frac{t - kT_{POW}}{DT_{POW}}\right) \quad (6)$$

$$PSD_{POW}(f) = V_{low}^2 \delta(f) + (V_{high} - V_{low})^2 (DT_{POW})^2 \text{sinc}^2(DT_{POW}f) \sum_{k=-\infty}^{\infty} \delta(t - k\Delta f) \quad (7)$$

While the Square POW's longer peak voltages facilitate envelope detection, the sharp corners and flat edges in the time-domain result in large bandwidth (Trotter & Durgin, 2010b). The Square POW peak power, average power, and PAPR are:

$$\text{peak power} = V_{high}^2 \quad (V^2) \quad (8)$$

$$\text{average power} = V_{high}^2 D + V_{low}^2 (1 - D) \quad (V^2) \quad (9)$$

$$\text{PAPR} = \frac{1}{D + (V_{low}^2 / V_{high}^2)(1 - D)} \quad (10)$$

Peak power is directly proportional to the square wave's high voltage, V_{high} . For large duty cycles, D, the average power will approximately equal the peak power yielding a low PAPR and ineffective POW. One period of the Square POW's equivalent time-domain representation is illustrated in Figure 2(c). The Square POW's PSD is illustrated in Figure 2(d).

C. POW Gain Over a Charge Pump Network

Passive RFID tags are self-powered by rectifying the RF input and multiplying the voltage through a charge pump network. A limiting factor of charge pump efficiency is the turn-on voltage of the pump's diodes. As a consequence, the DC output voltage of a Dickson charge pump is largely dependent on the maximum instantaneous voltage (V_i) of the input waveform. The POW Gain (G_{POW}) is defined as the ratio of DC power output of a POW input ($P_{out,POW}$) to DC power output of a CW input ($P_{out,CW}$). An approximate model that relates POW Gain to Peak-to-Average-Power Ratio (PAPR), peak voltage (V_i), and transmit power (P_t) is:

$$G_{POW} = \frac{P_{out,POW}}{P_{out,CW}} = \left(\frac{\sqrt{PAPR} - V_t / \sqrt{P_t}}{\sqrt{2} - V_t / \sqrt{P_t}} \right)^2 \quad (11)$$

This model applies only in the operating region where the diodes are forward-biased. This condition is met when $V_{ON} \leq V_i < V_b$, where V_{ON} is the diode turn-on voltage and V_b is the diode breakdown voltage. As the transmit power is increased, Eq. 11 tends toward $\text{PAPR}/2$, the empirical POW gain limit. In subsequent work, Trotter further develops and discusses a more holistic POW gain model comprised of 4-input power regions (2010).

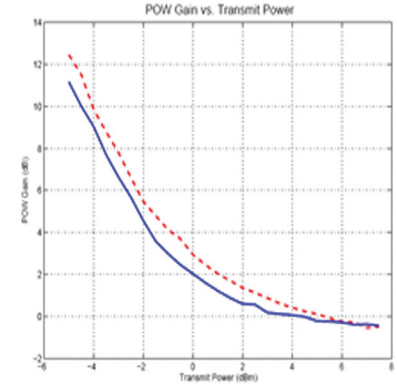


Figure 3. POW gain at different transmit powers for the 1-POW (solid line) and Square POW (dotted line). At 1 MHz frequency spacing, the 1-POW and the Square POW achieve positive gains at transmit powers below 4.5 dBm and 5.5 dBm, accordingly.

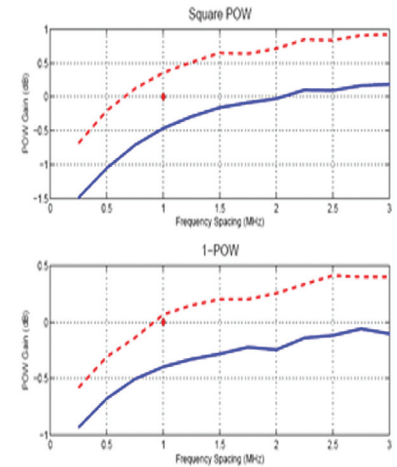


Figure 4. POW gain at different subcarrier frequency spacing for the Square POW (top) and 1-POW (bottom) at a transmit power of 4 dBm (dotted lines) and 7 dBm (solid lines). The Square POW and 1-POW with subcarrier frequency spacing of 1 MHz cross the 0 dB POW Gain point at 5.5 dBm and 4.5 dBm transmit powers, accordingly (marked by the diamonds).

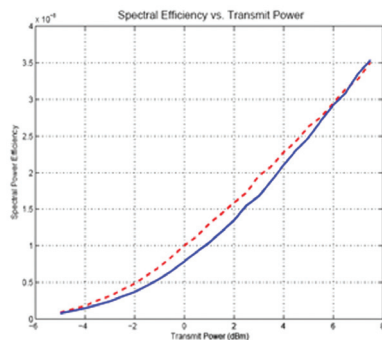


Figure 5. POW spectral efficiency at transmit power of -5 dBm to 7.5 dBm.

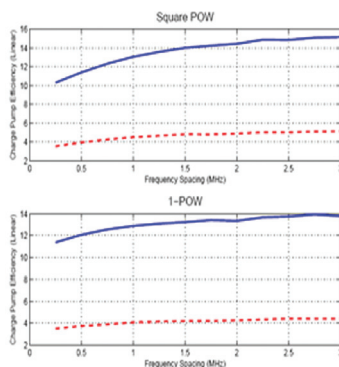


Figure 6. Charge pump efficiency at different frequency spacing for Square POW (top) and 1-POW (bottom) at a transmit power of 4 dBm (dotted lines) and 7 dBm (solid lines).

III. RESULTS

The Square POW and the 1-POW were compared along four dimensions:

- Gain versus transmit power
- Spectral power efficiency versus transmit power
- Gain versus POW frequency spacing
- Charge pump efficiency versus POW frequency spacing

Based on these parameters, the Square POW yielded an overall superior performance to the 1-POW.

The Square POW produced greater gain than the 1-POW at all transmit powers below 6.0 dBm. Within transmit powers of -5.0 dBm – 4.0 dBm, the Square POW averaged 1.13 dB gain over the 1-POW. As illustrated in Figure 3, the Square and 1-POW yielded negative gains beyond 5.5 dBm and 4.5 dBm, respectively. Saturation of the charge pumps for both POWs may account for the decaying gain as transmit power was increased.

Charge pump saturation might also explain the 0.78 dB and 0.45 dB drop in gains (Figure 4) for the Square POW and 1-POW, respectively, when transmit power was increased from 4 dBm to 7 dBm. Despite these drops in gain, Figure 4 illustrates a positive trend in POW gains as frequency spacing was increased. The Square POW yielded the greatest gains across the entire tested frequency spacing range of 250 kHz – 3 MHz.

The spectral power efficiency was calculated by holding the POW frequency constant and measuring the output voltage over a transmission power range of -5 dBm – 7.5 dBm. Since the POW bandwidth was kept constant, then the spectral power efficiency was expected to increase so long as output power increased. Figure 5 confirms that transmit power is proportional to spectral power efficiency.

Charge pump efficiency was calculated by holding the POW transmit power constant and measuring the output gain over a frequency spacing range of 250 kHz – 3 MHz. Each POW was tested at transmit powers of 4 dBm and 7 dBm. As illustrated in Figure 6, increasing frequency spacing resulted in higher POW gain regardless of transmit power. The Square POW exhibited 8.97% improvement in charge pump efficiency when transmit power was increased from 4 dBm to 7 dBm. The 1-POW exhibited a comparable improvement of 8.94% for the same increase in transmit power. At best, the Square POW yielded a marginally greater charge pump efficiency than the 1-POW; the more significant advantage of the Square POW was seen in gain over fixed frequency spacing at variable transmit powers (refer to Figure 3). The POW gain over the measured transmit power range is summarized in Table I.

IV. DISCUSSION

Improving the read range of passive RFID tags is advantageous in low-power applications ($P_t < 5$ dBm). The Square and 1-POW provide strictly positive gains at transmit powers of up to 5.5 dBm and 4.5 dBm, respectively. For applications operating under these transmit powers, both POWs yield greater read ranges than the CW signal. Furthermore, the Square POW produces higher gain at a majority of the tested transmit powers (refer to Figure 3). If the objective is to maximize read range at transmit powers beyond 5.5 dBm, alternative modulation schemes are necessary.

As observed in Figure 4, lower transmit powers yield positive POW gains over CW if the frequency spacing is sufficiently large. The Square POW, transmitting at 4 dBm, achieves positive gain when subcarrier frequency spacing is greater than 657 kHz. At 7 dBm, the frequency spacing needs to exceed 2.06 MHz in order to achieve positive gains. The 1-POW transmitting at a power of 4 dBm achieves positive gain if frequency spacing exceeds 917 kHz (260 kHz greater than the Square POW) but yields strictly negative gains at any frequency spacing below 3 MHz when transmitting at a power of 7 dBm. This helps confirm that a lower frequency spacing, or larger POW period, effectively reduces the frequency of POW peak voltage arrivals and therefore the energy harvesting charge pumps discharge for longer periods of time, resulting in reduced gains. Conversely, greater frequency spacing produces lower POW periods and higher frequency of peak voltage arrivals at the charge pumps. The flattening trends in Figure 4, however, suggest decreasing marginal gain with increasing frequency spacing. In light of the fact that the Federal Communications Commission (FCC) regulates RFID UHF bandwidth and limits its range in North America to 902 MHz – 928 MHz, a spectrally efficient POW should be designed with a frequency spacing that operates at positive gain over CW and still meets governmental restriction on signal bandwidth (Trotter & Durgin, 2010b).

While the current testbed measurements confirm some of the performance expectations for the 1-POW and the Square POW, some changes are suggested in future POW testing. The analytical derivation of the relation between frequency spacing and POW gain should be tested by extending the frequency spacing range beyond 3 MHz and confirming the theoretical POW gain limit, (PAPR/2). Another concern is that increased transmit powers yield improved charge pump efficiency despite reduced POW gains (Figure 6). A possible explanation is reflections at the charge pump input power interface which were unaccounted for. Therefore, the testbed should also incorporate a power coupler and power meter at the interface to account for reflection losses.

Table I
Measured POW Gain

Gain	Square POW	1-POW
Positive (+)	$-5.0 < P_t \leq 5.5$ dBm	$-5 < P_t \leq 4.5$ dBm
Negative (-)	$5.5 < P_t \leq 7.5$ dBm	$4.5 < P_t \leq 7.5$ dBm

If the **OBJECTIVE** is to **MAXIMIZE** read range at **TRANSMIT POWERS BEYOND 5.5 dBm**, alternative modulation schemes are **NECESSARY**.

V. CONCLUSION

Dickson charge pumps see increased DC output when powered by Power Optimized Waveforms (POWs). The experimental 1-POW and Square POW at transmit powers under 5 dBm yield a positive gain over conventional CW. The DC output power harvested by the Dickson charge pumps can be used to power passive tags such as those commonly found in RFID. The additional DC power extracted from POW at low transmit powers translates to greater transmission distances between RF transmitters and tags. The added efficiency makes this signal transmission method more desirable for its power-harvesting advantages in low-power RFID applications that can range from personal wireless battery chargers to communications and powering in industrial settings.

The **ADDED EFFICIENCY** makes this signal transmission method **MORE DESIRABLE** for its **POWER-HARVESTING ADVANTAGES** in low-power RFID applications that can range from **PERSONAL WIRELESS BATTERY CHARGERS** to **COMMUNICATIONS** and **POWERING** in industrial settings.

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